

Gamma-ray Emission From Advection-Dominated Accretion Flows Around Black Holes: Application to the Galactic Center

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ABSTRACT

We calculate the flux and spectrum of γ -rays emitted by a two-temperature advection-dominated accretion flow (ADAF) around a black hole. The γ -rays are from the decay of neutral pions produced through proton-proton collisions. We discuss both thermal and power-law distributions of proton energies and show that the γ -ray spectra in the two cases are very different. We apply the calculations to the γ -ray source, 2EG J1746-2852, detected by EGRET from the direction of the Galactic Center. We show that the flux and spectrum of this source are consistent with emission from an ADAF around the supermassive accreting black hole Sgr A* if the proton distribution is a power-law. The model uses accretion parameters within the range made likely by other considerations. If this model is correct, it provides evidence for the presence of a two temperature plasma in Sgr A*, and predicts γ -ray fluxes from other accreting black holes which could be observed with more sensitive detectors.

1. Introduction

Advection-dominated accretion flows (ADAFs) are optically thin hot accretion flows with low radiative efficiency (Narayan & Yi 1994, 1995 a,b; Abramowicz et al. 1995). Unlike standard thin disks (see Frank et al. 1992) in which the viscously generated energy is thermalized and radiated locally, ADAFs store most of the viscous energy and advect it into the central star. The gas in ADAFs has a two temperature structure (Shapiro, Lightman, & Eardley 1976; Rees et al. 1982), with the ions being hotter than the electrons. The viscous heating affects mainly the ions, the more massive species, while the radiation is produced primarily by the electrons. Since the ions transfer only a small fraction of their energy to the electrons via Coulomb scattering, the energy which

is radiated is much less than the total energy released during accretion (Rees et al. 1982).

The emission spectrum of an ADAF is mainly determined by the cooling processes of the electrons, viz. synchrotron, bremsstrahlung, and Compton processes (see eg. Narayan & Yi 1995b; Mahadevan 1997). Detailed calculations (e.g. Narayan 1996) show that ADAFs around accreting black holes have a characteristic spectrum ranging from radio frequencies $\sim 10^{10}$ Hz up to hard X-ray frequencies $\sim 10^{21}$ Hz, whose shape is a function primarily of the mass accretion rate, and to some extent the mass of the accreting star. A number of accreting black hole systems have been shown to contain ADAFs (e.g. Narayan, Yi, & Mahadevan 1995; Narayan, McClintock, & Yi 1996; Lasota et al. 1996, Fabian & Rees 1995, Mahadevan 1997, Narayan, Barret, & McClintock 1997, Reynolds et al. 1997).

In the work done so far, on ADAFs, only the cooling of the electrons has been considered in calculating the spectra. However, since ADAFs are two temperature plasmas with very high ion temperatures, e.g. $T_i \sim 10^{12}$ K close to a black hole (Narayan & Yi 1995b), one wonders if there might be radiative processes associated directly with the ions. In particular, at such high temperatures, collisions between protons can lead to substantial production of neutral pions, π^0 , which would decay into high energy ~ 70 MeV γ -rays. Charged pions can also be produced by proton-proton collisions, but the final decay products are neutrinos and electrons (and their anti-particles), so that most of the energy leaves the plasma either in neutrinos or lower energy photons.

Gamma-ray emission from a two temperature gas accreting onto a black hole has been computed previously (see e.g. Dahlbacka, Chapline, & Weaver 1974; Colpi, Maraschi, & Treves 1986, Berezhinsky & Dokuchaev 1990). Most of the previous work considered a thermal distribution of protons, and the predicted γ -ray fluxes depend sensitively on the particular accretion scenario being considered. In this paper we consider both thermal and non-thermal distributions of protons and focus specifically on the ADAF paradigm. Using the methods described by Dermer (1986ab) we calculate the flux and spectrum of γ -ray emission from ADAFs and show that these flows produce interesting levels of high energy γ -rays. In the case of the source Sagittarius A* (Sgr A*) at the Galactic Center, we predict a γ -ray flux which is above the sensitivity limit of the EGRET detector on the Compton Gamma-Ray Observatory, and we compare the prediction with a possible detection of this source.

The outline of the paper is as follows. In §2 we present the reaction rate for pion production and describe the structure and basic equations of ADAFs. In §3 we calculate the γ -ray spectra from thermal and non-thermal distributions of protons in ADAFs, and in §4 we apply these results to EGRET observations of the Galactic Center. In §5 we discuss other applications of the results.

2. General Relations

2.1. Pion Production

The production of γ -rays from $p - p$ collisions is a two step process, and has been worked out in detail by Stecker (1971, see also Stephens & Badhwar 1981; Dermer 1986ab). The colliding protons produce an intermediate particle, a neutral pion, π^0 , which then decays into two γ -ray photons. The reaction is

$$p + p \rightarrow p + p + \pi^0, \quad (1)$$

$$\pi^0 \rightarrow \gamma_1 + \gamma_2, \quad (2)$$

where the photons, γ_1 , γ_2 , in general have different energies in the gas frame. The number of neutral pions produced is calculated by considering two protons with four momenta p_1 and p_2 , moving towards each other with relative velocity v_{rel} . The number of collisions that occur in a volume dV , for a time dt , is a frame invariant quantity, which in an arbitrary reference frame can be written as (see Landau & Lifshitz 1975, §12)

$$dR_{12} = \sigma v_{\text{rel}} \frac{p_1 \cdot p_2}{E_1 E_2} n_1 n_2 dV dt, \quad (3)$$

$$= c\sigma n_1 n_2 \sqrt{(\vec{\beta}_1 - \vec{\beta}_2)^2 - (\vec{\beta}_1 \times \vec{\beta}_2)^2} dV dt. \quad (4)$$

Here, n_1 , n_2 are the number densities of the protons, E_1 , E_2 are their energies, σ is the total cross-section for pion production, and $\vec{\beta}_1$, $\vec{\beta}_2$ are the respective velocity parameters of the two particles. For a distribution of particle velocities, the total number of pions produced per second is just the integral of dR_{12} over volume and velocities, which in spherical co-ordinates is

$$\begin{aligned} N(E_\pi) &= 2\pi c \int R^2 dR \int_1^\gamma d\gamma_1 \int_\gamma^\infty d\gamma_2 \int_{-1}^1 d\cos\theta \\ &\times \sigma(\gamma_1, \gamma_2, \cos\theta) n(R, \gamma_1) n(R, \gamma_2) \sqrt{(\vec{\beta}_1 - \vec{\beta}_2)^2 - (\vec{\beta}_1 \times \vec{\beta}_2)^2} \text{ s}^{-1}, \end{aligned} \quad (5)$$

where γ_1 , γ_2 are the respective Lorentz factors of the two protons, $\cos\theta = \vec{\beta}_1 \cdot \vec{\beta}_2 / |\vec{\beta}_1| |\vec{\beta}_2|$, and R is the radius with respect to the accreting star. The total number of γ -rays produced is $2 N(E_\pi)$.

To obtain the γ -ray spectrum, we first calculate the spectrum of pion energies, $F(E_\pi) dE_\pi$, in the frame of the observer. The observed γ -ray spectrum is then obtained through the relation (Stecker 1971)

$$F(E_\gamma) = 2 \int_{E_{\pi\text{min}}}^\infty dE_\pi \frac{F(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}} \text{ photons s}^{-1} \text{ GeV}^{-1}, \quad (6)$$

where $m_\pi = 0.135 \text{ GeV}/c^2$ is the mass of the pion, and $E_{\pi\min}$ is the minimum pion energy required to produce a γ -ray with energy E_γ ,

$$E_{\pi\min} = E_\gamma + \frac{m_\pi^2}{4 E_\gamma^2}. \quad (7)$$

The pion spectrum, $F(E_\pi)$ is obtained by substituting the differential cross-section $d\sigma(E_\pi; \gamma_1, \gamma_2, \cos\theta)/dE_\pi$ for $\sigma(\gamma_1, \gamma_2, \cos\theta)$ in equation (5). Two models are generally used to determine the differential cross-section for pion production: the isobar model and the scaling model. In the isobar model, pions are produced by a two step process. Colliding protons produce an isobar, with rest mass 1.238 GeV, which subsequently decays into a proton and a pion (Lindenbaum & Sternheimer 1957; Stecker 1971). Dermer (1986b) has shown that the isobar model agrees with the experimental data quite well for proton energies near threshold: $E_p \lesssim 4 \text{ GeV}$. On the other hand, for proton energies $E_p \gtrsim 8 \text{ GeV}$, the scaling model of Stephens and Badhwar (1981) represents the experimental data better (Dermer 1986b). In our calculations, we therefore use the two models in their respective ranges of validity and interpolate smoothly (cubic interpolation) in the intermediate regime.

2.2. ADAF Equations

To evaluate equations (5) and (6) we need the number density of protons as a function of energy in the accretion flow, $n_p(R, \gamma)$. We write $n_p(R, \gamma)$ as the product of a normalized velocity distribution, which depends on the temperature at a given radius, and the total number density of protons,

$$n_p(R, \gamma) = n_p(R) n_\gamma[\gamma, \theta_p(R)], \quad (8)$$

with

$$\int_1^\infty n_\gamma[\gamma, \theta_p(R)] d\gamma = 1, \quad \int_1^\infty (\gamma - 1) n_\gamma[\gamma, \theta_p(R)] d\gamma = \frac{3}{2} \theta_p(r). \quad (9)$$

Here, $\theta_p(R)$ is the dimensionless ion temperature, $\theta_p = kT_i/m_p c^2$, at radius R .

An ADAF is characterized by four parameters: the viscosity parameter, α (Shakura & Sunyaev 1973), the ratio of gas pressure to total pressure, β_{adv} , the mass of the central black hole, M , and the mass accretion rate, \dot{M} . Given these parameters, the global structure and dynamics of ADAFs can be calculated (Narayan, Kato, & Honma 1997; Chen, Abramowicz, & Lasota 1997). Generally, ADAFs appear to have large values of $\alpha \gtrsim 0.1$ (Narayan 1996), and the uncertainty in the value is a factor of a few. Many published ADAF models in the literature use $\alpha = 0.3$ (e.g. Narayan et al. 1996, 1997). If there is equipartition between magnetic and gas pressure, we expect $\beta_{\text{adv}} = 0.5$; this

is the value we favor. However, for completeness we also consider the more extreme case $\beta_{\text{adv}} = 0.95$, where the magnetic pressure contributes negligibly ($\sim 1/20$) to the total pressure.

The radial structure of ADAFs is well approximated by a series of concentric spherical shells, with the properties of the gas varying as a function of radius (Narayan & Yi 1995a). The continuity equation gives $\dot{M} = 4\pi R^2 v(R) \rho(R)$, where $v(R)$ is the radial velocity of the gas, and $\rho(R)$ is the mass density. Writing the radius in units of the Schwarzschild radius, $r = R/R_S$, where $R_S = 2.95 \times 10^5 m \text{ cm}$ and $m = M/M_\odot$ is the mass of the central star in solar mass units, and assuming that the mass fraction of hydrogen is $X = 0.75$, we have

$$\begin{aligned} n_p(r) &= \frac{X \rho(r)}{m_p} = 1.9 \times 10^{19} m^{-1} \dot{m} r^{-2} \left[\frac{v(r)}{c} \right]^{-1}, \\ &\equiv m^{-1} \dot{m} \tilde{n}(r) \text{ cm}^{-3}. \end{aligned} \quad (10)$$

Here $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$ is the accretion rate in Eddington units, with $\dot{M}_{\text{Edd}} = 1.39 \times 10^{18} m \text{ g s}^{-1}$, and $\tilde{n}(r)$ is defined so as to scale out the dependence of $n_p(r)$ on m and \dot{m} . Given α , β_{adv} , m and \dot{m} , equation (10) allows us to calculate $n_p(r)$ provided we have $v(r)/c$. We obtain $v(r)/c$ from the global ADAF solution of Narayan et al. (1997).

The ion temperature $T_i(r)$ is obtained from the total gas pressure p_g (Narayan & Yi 1995b),

$$p_g = \beta_{\text{adv}} \rho(r) c_s^2(r) = \frac{\rho(r) k T_i}{\mu_i m_p} + \frac{\rho(r) k T_e}{\mu_e m_p}, \quad (11)$$

where $c_s(r)$ is the isothermal sound speed, and $\mu_i = 1.23$, $\mu_e = 1.14$ are the effective molecular weights of the ions and electrons respectively. Since $T_i \gg T_e$ we neglect the second term to obtain

$$T_i(r) = 1.34 \times 10^{13} \beta_{\text{adv}} \left[\frac{c_s(r)}{c} \right]^2 \text{ K}, \quad (12)$$

where c is the velocity of light. We obtain $c_s(r)/c$ again from the global solution of the ADAF (Narayan et al. 1997).

Given $n_p(r)$ and $T_i(r)$ and an assumed functional form for the proton energy distribution $n_\gamma(\gamma, \theta_p)$, we can substitute equation (8) in equations (5) and (6) to calculate the γ -ray spectrum.

3. Results

At present our understanding of viscous heating is poor, and we do not know whether the process leads to a thermal or power-law distribution of proton energies, or

perhaps some combination of the two. In this section we calculate the pion spectra by considering two different proton energy distributions: a relativistic Maxwell–Boltzmann distribution and a power–law distribution.

3.1. Thermal Distribution

The proton temperature in an ADAF close to a black hole is marginally relativistic, $\theta_p = k T_p / m_p c^2 \lesssim 0.2$. At such temperatures, pions are produced primarily by protons in the tail of the Maxwell–Boltzmann distribution, since only these particles have energies above the threshold needed for pion production. Thus, the pion production is very sensitive to the proton temperature, and since θ_p scales approximately as $1/r$ (Narayan & Yi 1995b; Mahadevan 1997), most of the production is from the innermost radii of the ADAF, $r \lesssim 10$.

The protons at these temperatures have momenta near the threshold for pion production, and do not exceed $\sim 1 \text{ GeV}/c$. At such energies the isobar model (Lindenbaum & Sternheimer 1957; Stecker 1971; Dermer 1986a) is more accurate and we have therefore used it to calculate the cross–sections and energy spectra. In this model, the isobars move along the initial directions of the colliding protons in the center of momentum (CM) system. It is therefore convenient to transform variables in equation (5) via a Lorentz boost to the CM reference frame, followed by a rotation so that the colliding protons are moving along the z–axis (Dermer 1984, 1986a). Using equation (5) with equation (10), and rewriting in terms of the new variables (see Dermer 1984, 1986a for details), we obtain

$$\begin{aligned}
 F(E_\pi) &= \frac{(2.95 \times 10^5)^3 m \dot{m}^2 \pi c}{m_\pi} \int_1^{r_{\max}} dr \frac{r^2 \tilde{n}^2(r)}{\theta_p(r) K_2^2[1/\theta_p(r)]} \int_1^\infty d\gamma_r \frac{(\gamma_r^2 - 1)}{[2(\gamma_r + 1)]^{1/2}} \\
 &\times \int_1^{\zeta/m_\pi} \frac{d\gamma^*}{\gamma^* \beta^*} \frac{d\sigma^*(\gamma^*; \gamma_r)}{d\gamma^*} \{ \exp[-q\gamma\gamma^*(1 - \beta\beta^*)] - \exp[-q\gamma\gamma^*(1 + \beta\beta^*)] \}, \\
 &\text{photons s}^{-1} \text{ GeV}^{-1}.
 \end{aligned} \tag{13}$$

Here $E_\pi = m_\pi \gamma$ is the pion energy in the observer’s frame, $\gamma_r = \gamma_1 \gamma_2 (1 - \beta_1 \beta_2 \cos \theta)$ is the relative Lorentz factor of the two colliding protons, $q \equiv [2(\gamma_r + 1)]^{1/2} / \theta_p(r)$, $d\sigma^*(\gamma^*; \gamma_r)/d\gamma^*$ is the differential cross–section for the production of a pion with Lorentz factor γ^* in the CM frame for a given γ_r , $\zeta \equiv (S - 4m_p^2 + m_\pi^2)/S^{1/2}$ where $S = 2m_p^2(\gamma_r + 1)$ characterizes the strength of the collision, $K_2(1/\theta_p)$ is the modified Bessel function of order 2, and we have used a Maxwell–Boltzmann energy distribution for the protons. We take r_{\max} to be 10^3 ; however, since the proton temperature decreases steeply with radius ($T_i \sim 1/r$) the contribution to the pion spectrum from the gas at $r > 30$ is negligible.

The calculation in equation (13) gives the pion spectrum, $F(E_\pi)$. Using equation (6), we then obtain the γ –ray spectrum. The results are shown in Fig. 1. The plot

corresponds to two values of the viscosity parameter α , 0.1 and 0.3, and two values of β_{adv} , 0.5 and 0.95. For a given α , increasing β_{adv} leads to increasing gas pressure, and therefore to increasing ion temperature (see eq. 12). Changing β_{adv} from 0.5 to 0.95 causes the temperature to go up by a factor ~ 2 , and since the pion production is extremely sensitive to temperature, the γ -ray luminosity increases by nearly two orders in magnitude. Changes in α also affect the γ -ray luminosity, though less sensitively. Since the total luminosity is proportional to n_p^2 which varies roughly as α^{-2} (Narayan & Yi 1995b), we might expect the luminosity to increase with decreasing α . This effect is counterbalanced however by small changes in the temperature, and the luminosity in fact decreases slightly when α goes down from 0.3 to 0.1.

3.2. Non-Thermal Distribution

In this section we consider a power-law distribution of proton energies described by a spectral index s . Equation (10) continues to hold, but $n[\gamma, \theta_p(r)]$ is no longer a Maxwell-Boltzmann distribution. To determine the form of $n[\gamma, \theta_p(r)]$, two requirements have to be satisfied (see eq. 9), namely the normalization condition and the requirement that the average kinetic energy of the power-law distribution of protons, at each radius, be equal to the average energy of the protons as given by the local ion temperature.

We model the energy distribution of protons as

$$n[\gamma, \theta_p(r)] d\gamma = \left\{ [1 - \zeta(r)] \delta(\gamma - 1) + (s - 1) \zeta(r) \gamma^{-s} \right\} d\gamma, \quad (14)$$

where a fraction $1 - \zeta(r)$ of the protons have $\gamma \sim 1$, and a fraction $\zeta(r)$ are in a power-law tail with index s . The distribution is properly normalized. The fraction $\zeta(r)$ is fixed by the energy requirement:

$$\zeta(r) = \frac{3}{2} (s - 2) \theta_p(r). \quad (15)$$

Since the exact energy distribution for the fraction $1 - \zeta(r)$ of protons with energy below threshold is not important for the present calculation, we have simplified the distribution to a δ function in equation (14).

To calculate the total pion luminosity, $N(E_\pi)$, we substitute equation (14) in equation (5). We then obtain three different terms proportional to $(1 - \zeta)^2$, $(1 - \zeta)\zeta$, and ζ^2 , respectively. The $(1 - \zeta)^2$ term gives no contribution since it corresponds to protons with $\gamma \sim 1$ colliding with one another. These protons do not have enough energy to produce pions. The $(1 - \zeta)\zeta$ term corresponds to protons with $\gamma > 1$ colliding with protons with $\gamma \sim 1$, and we denote the contribution by $N_1(E_\pi)$. Similarly, the ζ^2 term corresponds to protons with $\gamma > 1$ colliding with protons with $\gamma > 1$, and we denote it

as $N_2(E_\pi)$. We have

$$\begin{aligned} N_1(E_\pi) &= 4\pi c(2.95 \times 10^5)^3 m \dot{m}^2 (s-1) \int dr r^2 \tilde{n}^2(r) [1 - \zeta(r)] \zeta(r) \\ &\times \int_1^\infty \sigma(\gamma) \gamma^{-s} \beta d\gamma, \\ &\equiv m \dot{m}^2 I(s, \alpha, \beta_{\text{adv}}) \int_1^\infty \sigma_{\text{mb}}(\gamma) \gamma^{-s} \beta d\gamma \quad s^{-1}, \end{aligned} \quad (16)$$

and

$$\begin{aligned} N_2(E_\pi) &= 4.84 m \dot{m}^2 (s-1)^2 \int dr r^2 \tilde{n}^2(r) \zeta^2(r) \int_1^\gamma d\gamma_1 \gamma_1^{-s} \int_\gamma^\infty d\gamma_2 \gamma_2^{-s} \\ &\times \int_{-1}^1 d(\cos\theta) \sigma_{\text{mb}}(\gamma_1, \gamma_2, \cos\theta) \sqrt{(\vec{\beta}_1 - \vec{\beta}_2)^2 - (\vec{\beta}_1 \times \vec{\beta}_2)^2} \quad s^{-1}, \end{aligned} \quad (17)$$

where σ_{mb} is the cross-section in units of millibarns, and

$$I(s, \alpha, \beta_{\text{adv}}) \equiv 9.68 (s-1) \int dr r^2 \tilde{n}^2(r) [1 - \zeta(r)] \zeta(r). \quad (18)$$

In an ADAF, we generally have $\zeta \ll 1$ so that most of the protons have $\gamma \sim 1$ (cf. eq. 15). We therefore expect most of the pion production and γ -ray luminosity to come from $N_1(E_\pi)$. Table 1 gives numerical results and we see that $N_2(E_\pi)$ is indeed negligible compared with $N_1(E_\pi)$.

In calculating the pion spectrum, we consider only the contribution from $N_1(E_\pi)$ and write

$$\begin{aligned} F(E_\pi) &\simeq \frac{dN_1(E_\pi)}{dE_\pi} \\ &= \frac{I(s, \alpha, \beta_{\text{adv}}) m \dot{m}^2}{m_\pi} \int_1^\infty d\gamma \gamma^{-s} \beta \frac{d\sigma_{\text{mb}}(\gamma_\pi, \gamma)}{d\gamma_\pi}, \quad \text{photons s}^{-1} \text{ GeV}^{-1}. \end{aligned} \quad (19)$$

Unlike in the case of a thermal distribution where most of the protons have energies either below or just above threshold, in a power-law distribution the protons have a wide range of energy and some protons are well above threshold. We therefore use both the isobar and scaling models, as described in §2.1.

Equation (19) reveals the dependence of the pion flux and energy spectrum on the parameters: (1) The flux is proportional to $m \dot{m}^2$. (2) The flux depends on α , β_{adv} and s through the function $I(s, \alpha, \beta_{\text{adv}})$ defined in equation (18). (3) The shape of the spectrum depends only on s and is given by the integral in equation (19).

Tables 2 and 3 give $I(s, \alpha, \beta_{\text{adv}})$ for different values of its parameters. For fixed α , increasing β_{adv} leads to increasing $I(s, \alpha, \beta_{\text{adv}})$ since the temperature in the flow increases. However, unlike the thermal case, the luminosity is not excessively sensitive to β_{adv} since the number of protons above threshold is directly proportional to θ_p (cf. eq. 15); therefore, a change in β_{adv} by a factor of two changes the total luminosity only by ~ 2 . For fixed β_{adv} in a self-similar solution (Narayan & Yi 1994, 1995b), the density

varies in proportion to α^{-1} , so the luminosity scales as α^{-2} . However, in the more accurate global solutions employed in this paper, the dependence of density—and hence luminosity—on α is not strictly a power-law, and the overall strength of the dependence is somewhat weaker than in the self-similar solutions. To illustrate this dependence, we list the numerical values of $I(s, \alpha, \beta_{\text{adv}})$ for three different choices of α in Tables 2 and 3.

Figure 2 shows γ -ray spectra for different values of the proton energy spectral index s (we fix $\alpha = 0.3$, $\beta_{\text{adv}} = 0.5$). The γ -ray spectral index at high energies $E_\gamma \gtrsim 1$ GeV is the same as the energy spectral index of the protons s , as shown by Dermer (1986b). For this reason, we investigated values of s in the range 2.3 – 3.3. The spectrum turns over at $E_\gamma \sim 70$ MeV (approximately half the pion rest mass) and falls for lower photon energies. Comparing Figures 1 and 2, we see that the total γ -ray luminosity from a power-law energy distribution of protons is comparable to that obtained from a thermal distribution when $\beta_{\text{adv}} = 0.95$, but is very much higher for $\beta_{\text{adv}} = 0.5$. In our view $\beta_{\text{adv}} = 0.5$ is the natural choice since it corresponds to equipartition between gas and magnetic pressure. The γ -ray spectrum extends to much higher photon energies when the protons have a power-law distribution compared to the thermal case.

4. Application to Sgr A*

The black hole candidate at the center of our Galaxy, Sagittarius A* (Sgr A*), appears to be a scaled down version of an AGN. The source is believed to consist of a black hole of mass $M = 2.45 \times 10^6 M_\odot$ (Eckart & Genzel 1996a, 1996b) accreting gas from its surroundings.

The mass accretion rate in Sgr A* has been estimated by various methods (see Genzel et al. 1994 for a summary). The accretion of wind gas from neighboring stars (principally IRS 16) seems to be the most likely scenario. The accretion rate is determined by considering the fraction of the wind that comes within the accretion radius of the central black hole, but the estimate depends sensitively on the assumed wind velocity. Genzel et al. (1994) obtain an accretion rate of $\dot{M} \simeq 6 \times 10^{-6} M_\odot / \text{yr}^{-1}$ which corresponds to $\dot{m} \sim 10^{-4}$ for $M = 2.45 \times 10^6 M_\odot$, assuming a wind velocity of 1000 km s $^{-1}$ and mass loss rate from winds of $\sim 3.5 \times 10^{-3} M_\odot / \text{yr}^{-1}$. Melia (1992) uses a wind velocity of 600 km s $^{-1}$ and obtains an accretion rate of $\dot{M} \simeq 2 \times 10^{-4} M_\odot / \text{yr}^{-1}$ ($\dot{m} \sim 3 \times 10^{-3}$). The true accretion rate probably lies between these two estimates, and we will require our models to have $10^{-4} < \dot{m} < 3 \times 10^{-3}$. Note that Lacy et al. (1982; see also Rees 1982) estimated a much higher mass accretion rate of $\dot{M} \simeq 2 \times 10^{-3} M_\odot / \text{yr}^{-1}$ from stellar disruptions at the Galactic Center, but argued that the accretion due to this probably has a low duty cycle.

Sgr A* has an extremely low luminosity, $L \sim 10^{37} \text{ erg s}^{-1}$, which corresponds to $\dot{m} \sim 10^{-8}$ if the accretion flow has a standard radiative efficiency of 10%. Such a low \dot{m} is in serious conflict with the estimate of \dot{m} given in the previous paragraph. Narayan, Yi & Mahadevan (1995) suggested that Sgr A* does accrete at a rate near the one estimated, but in an advection-dominated mode. Using a self-similar ADAF model, they were able to reconcile the low luminosity of the source with a relatively large \dot{m} : $\sim 8 \times 10^{-4} \alpha$. If $\alpha > 0.1$, the accretion rate inferred on the basis of the ADAF model would be in agreement with that estimated on the basis of gas supply. Furthermore, they obtained a reasonable fit to the observed spectrum from radio to hard X-ray frequencies. In this section, we calculate the γ -ray luminosity and spectrum of Sgr A* due to pion production, and compare these predictions with the flux seen by EGRET from the direction of the Galactic Center.

Among several unidentified sources detected by EGRET in the Galactic plane (Merck et al. 1996), the source 2EG 1746-2852 is of particular interest since it is spatially coincident with the Galactic Center. There is no firm identification of this source, but it is point-like to within the resolution of the instrument ($\sim 1^\circ$), it is $\sim 10\sigma$ above the local diffuse emission, and its spectrum differs significantly from the spectra of other unidentified EGRET sources. Out of the 32 sources whose spectra are reported by Merck et al. (1996), 27 have spectral slopes > 2.0 (photon index), 4 have spectral slopes ~ 1.9 and one has a very hard spectrum with a spectral slope of 1.7. This last source is 2EG 1746-2852, and it is located exactly at the Galactic Center. Following Merck et al. (1996), we make the reasonable assumption that 2EG 1746-2852 corresponds to Sgr A*. Figure 3 shows the spectrum of the source as measured by EGRET. The dashed line is the best-fit power-law obtained by Merck et al. (1996) over the photon energy range 100–4000 MeV. Their fitted spectral slope is $s = 1.7 \pm 0.1$. At higher energies, the data suggest a roll-over in the spectrum which would give a softer spectral index at higher energies ($E \gg 4 \text{ GeV}$).

4.1. Thermal Distribution

Figure 3 compares the γ -ray spectrum from the thermal model with the EGRET data. The solid line corresponds to $\alpha = 0.3$, $\beta_{\text{adv}} = 0.95$, and the dotted line to $\alpha = 0.3$, $\beta_{\text{adv}} = 0.5$. The black hole mass is taken to be $m = 2.45 \times 10^6$, and the accretion rates in the two models have been varied such that the predicted spectra agree with the data point at $E \sim 200 \text{ MeV}$; the accretion rates are indicated on the plot.

It is clear that the thermal model predicts a spectrum with the wrong shape and fails to explain the EGRET detection at $E \sim 1 \text{ GeV}$. Moreover, for the preferred value of $\beta_{\text{adv}} = 0.5$, the model requires a rather high \dot{m} , which is much larger than the range

we consider reasonable (see above). We conclude that the thermal model is inconsistent with the observations.

4.2. Non-Thermal Distribution

Fig. 4 compares γ -ray spectra from various power-law models ($\alpha = 0.3, \beta_{\text{adv}} = 0.5$) with the EGRET data. The different curves correspond to different values of the proton energy index s . For each s , we have varied the accretion rate so as to obtain the closest agreement with the observed spectrum. The results ($5 \times 10^{-4} < \dot{m} < 9.2 \times 10^{-4}$), which are only weakly dependent on s , are given in Table 4. The accretion rates so inferred fall well within the range of accretion rates estimated on the basis of the properties of nearby gas ($10^{-4} < \dot{m} < 3 \times 10^{-3}$, Genzel et al. 1994), and are within factors of a few of the accretion rate estimated on the basis of fitting the radio to X-ray spectrum with the somewhat less accurate self-similar version of the ADAF model ($\dot{m} \sim 8 \times 10^{-4} \alpha$, Narayan, Yi, & Mahadevan 1995).

Reproducing the power-law portion of the γ -ray spectrum is a by-product of postulating a power-law proton energy distribution. However, it is striking in this context that the best-fit slope, $s \simeq 2.7$, is identical to the slope of the low-energy cosmic ray distribution. The models predict roll-overs at both the high energy (few GeV) and low energy ($\sim 200\text{MeV}$) ends of the spectrum. At the high-energy end there is just a hint of such a roll-over in the data, but at the low-energy end, the evidence seems somewhat stronger.

The similarity of the best-fit spectral shape to the diffuse Galactic γ -ray emission has two possible interpretations. First, since the diffuse emission is generally interpreted as being due to cosmic ray protons striking thermal protons in the interstellar medium, a mechanism similar to what occurs in an ADAF, the EGRET detection of 2EG 1746–2852 could be interpreted as cosmic ray protons colliding with a compact dense cloud of gas that is spatially coincident with the Galactic Center. This interpretation would require such a cloud to have a considerably greater gas density (and possibly also cosmic ray density) than in the interstellar medium only slightly farther away from the Galactic Center. If virtually all the Galactic Center region γ -ray flux were due to such a cloud, the power-law proton distribution function version of the ADAF model would be put seriously in doubt. Thermal proton distribution function versions of the ADAF model (or entirely different models) would not be seriously constrained if the γ -rays coming from the Galactic Center prove not to have their source in Sgr A*.

The alternative is that the observed γ -ray spectrum is in fact due to Sgr A*. In this case, not only is the deduced accretion rate roughly consistent with previous estimates, but we also have the interesting result that whatever process determines the cosmic

proton energy distribution (shock acceleration ?) is also at work in ADAFs. We find the numerical coincidence between the prediction of the power-law version of the ADAF model and the observed γ -ray flux striking enough to justify pursuing this interpretation.

To gauge just how strong the quantitative agreement is, we must consider how much freedom the model is given by adjustable parameters. Three free parameters are significant. One (\dot{m}) is fixed to within an order of magnitude or so by other considerations (the amount of gas available to accrete, and fitting the radio–X-ray spectrum). Another (α), while formally unconstrained over a range of several orders of magnitude, is often supposed to have a value quite near the one which we infer (i.e. between 0.1 and 1, cf. Narayan 1996). Only the third (s) is chosen almost entirely on the basis of fitting the observed γ -ray spectrum. Because the γ -ray luminosity predicted by the ADAF model (assuming a power-law proton energy distribution) approximately scales with $\dot{m}^2\alpha^{-1.5}$ (the actual scaling with α is only very roughly described by a power-law), the combined *a priori* uncertainty in \dot{m} and α may be regarded as giving the γ -ray luminosity predicted by the model a possible range of ~ 100 .

5. Discussion & Conclusions

Since it is not understood whether viscous heating produces a thermal or power-law distribution of proton energies, we have calculated the γ -ray emission of ADAFs corresponding to both types of distributions. We expect that the true energy distribution in any given source will be bracketed by these two extremes. Spectra corresponding to intermediate models can be easily calculated by taking a weighted sum of the thermal and power-law models.

If the proton distribution is thermal, the spectrum has a characteristic shape with a peak at $E_\gamma \sim 70$ MeV and very little emission at either lower or higher photon energies. For the kinds of proton temperatures expected in an ADAF, only a small fraction of the protons (in the tail of the Maxwellian distribution) have sufficient energy to produce pions. Consequently, even a minor change in the temperature, say by a factor of ~ 2 , can modify the γ -ray luminosity by orders of magnitude (cf. Figure 1). Since the flux is very sensitive to the gas temperature, a detailed understanding of the physics of the ADAF in the region $r \lesssim 10$ (where most of the γ -ray luminosity originates) is necessary in order to make testable predictions. The present study does not have the necessary accuracy for this. General relativistic effects become important at these radii and need to be included consistently. In principle, if these effects are included, the γ -ray spectrum could be used as a sensitive probe of the proton temperature. One might even hope to distinguish between rotating and non-rotating black holes, since the physical properties of the flow at $r \lesssim 10$ will be different for the two cases.

If the protons have a power-law distribution of energies, the γ -ray spectrum again peaks at ~ 70 MeV, but there is significant emission at higher photon energies. Indeed, the spectrum asymptotically has a spectral slope s which is equal to the power-law index s of the proton distribution (Dermer 1986b). Thus, the detection of a power-law γ -ray spectrum not only indicates the nonthermal nature of the protons but also helps determine the energy index.

In contrast to the thermal case, only half the γ -ray luminosity due to a power-law distribution of proton energies originates from $r \lesssim 10$, while the other half is emitted from $r \gtrsim 10$. Further, the luminosity is not very sensitive to changes in the temperature. Therefore, our present understanding of the physics of ADAFs is probably adequate for a reasonable estimate of the γ -ray flux, and we can thus test this version of the ADAF paradigm usefully against observations.

The Galactic Center source, Sgr A* presents an excellent opportunity to test the model, since there is a good case for the presence of an ADAF in this source (Narayan et al. 1995) and the predicted γ -ray flux is large enough to be detectable with current instruments. Indeed, EGRET has detected an unresolved source in the Galactic Center region, 2EG J1746-2852 (Merck et al. 1996). It is possible that this source corresponds to a dense compact gas cloud interacting with cosmic rays. However, the source could equally well be associated with Sgr A*. The γ -ray flux of Sgr A* which we calculate with our model using a power-law distribution of proton energies is in good agreement with the observed flux of 2EG J1746-2852 *given parameters which are almost determined on independent grounds*. In order to fit the flux, we need an Eddington-scaled mass accretion rate of $\dot{m} \sim 5\text{--}9 \times 10^{-4}$ (for $\alpha = 0.3$), close to the estimate $\dot{m} \sim 8 \times 10^{-4} \alpha$ obtained by Narayan et al. (1995) from fitting the lower energy spectrum due to the electrons. It is also compatible with the range of \dot{m} quoted by Genzel et al. (1994) on the basis of gas motions in the vicinity of Sgr A*: $10^{-4} < \dot{m} < 3 \times 10^{-3}$. In addition, the pion-decay model for the Galactic Center γ -ray spectrum predicts a roll over at energies below $\simeq 100$ MeV that may be present in the observed spectrum.

An exciting aspect of the present study is that it provides for the first time a direct probe of the protons in hot accretion flows. A fundamental assumption in ADAF models is that the plasma is two-temperature. However, until now there has been no direct test of this assumption since all previous investigations of the emission from ADAFs dealt only with the electrons. The γ -ray emission we have considered in this paper is due entirely to the protons. Moreover, it requires that the protons have nearly virial energies in order to be able to exceed the energy threshold for pion production. The encouraging results we have obtained in the case of Sgr A* indicate that this source might have a two-temperature plasma exactly as postulated in the models. More detailed study of Sgr A* coupled with future detections of other sources (see below), could strengthen the case for two-temperature accretion flows significantly.

Another exciting aspect of this study is that the γ -ray spectrum from pion de-

cay provides a direct window to the energy distribution of the protons. In the ADAF paradigm, viscous heat energy goes almost entirely into the protons. Furthermore, it is easy to show that, at least at the low \dot{m} expected in quiescent systems, the protons have no energetically important interactions either among themselves or with the electrons. Therefore, each proton retains memory of all the heating events it has undergone during the accretion, and so the energy distribution of the protons directly reflects the heating processes present in the plasma. In principle, with sufficiently sensitive observations, one could use γ -ray measurements as a direct probe of viscous heating. This would be invaluable for the theory of hot accretion flows.

The ADAF model has been applied successfully to several other low-luminosity black holes in addition to Sgr A*. The sources studied include two X-ray binaries in quiescence, A0620–00 and V404 Cyg (Narayan, McClintock, & Yi 1996, Narayan, Barret & McClintock 1997), and several quiescent AGNs, viz. the LINER galaxy NGC 4258 (Lasota et al. 1996, Herrnstein et al. 1996) and the nearby elliptical galaxies NGC 4472, NGC 4486, NGC 4649, and NGC 4636 (Mahadevan 1997; Reynolds et al. 1997). Table 5 gives the values of m , \dot{m} , α and β_{adv} of several of these systems (taken from the references indicated) and presents the expected γ -ray fluxes according to our model. Among the nearby ellipticals, we have included only NGC4486 since it is the only system with a reliable mass estimate (Ford et al. 1995; Harms et al. 1995). The γ -ray flux estimates in Table 5 assume that the protons have a power-law energy distribution with $s = 2.75$. We see that, only in the case of Sgr A* does the detection threshold of EGRET (10^{-8} photons $\text{cm}^{-2} \text{s}^{-1}$) permit a test of the predictions, although some of the other sources might be not far below the EGRET threshold. These sources are potentially detectable with future instruments such as the Gamma Ray Large Area Space Telescope (GLAST), which is designed to be 100 times more sensitive than EGRET.

Narayan (1996) has argued that X-ray binaries in the “hard state” (also called the “low state”) may also contain ADAFs with $\dot{m} \lesssim 0.1$. If the proton energy distribution in these sources is a power-law of the sort we suggest exists in Sgr A*, several of them might be expected to produce detectable γ -ray fluxes. However, the accretion rates in these objects (e.g. Cyg X-1) is likely to be close to the maximum rate permitting an ADAF (Narayan & Yi 1995b). If this is the case, particle interactions might be rapid enough that maintenance of a true power-law distribution function would be questionable. Accurate predictions of the γ -ray flux would then require a more elaborate calculation than we have performed for Sgr A*.

Finally, we note that in determining the γ -ray spectra, we have neglected gravitational redshift effects which become important at $r \lesssim 5$. We have also neglected the Doppler blueshift associated with the large radial and orbital velocities of the gas at these radii (Narayan & Yi 1995b). Only a detailed calculation can tell which of the two effects predominates. We note, however, that these effects are not likely to modify the results we have presented for a power-law distribution of protons because more than

half the emission in this case occurs at $r \gtrsim 10$.

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Table 1: Photon luminosities (photons s^{-1}) in units of $m\dot{m}^2$ for $\alpha = 0.3$, $\beta_{\text{adv}} = 0.5$, and different power-law indices s .

s	$\frac{N_1(E_\gamma)}{m\dot{m}^2}$	$\frac{N_2(E_\gamma)}{m\dot{m}^2}$	$\frac{N(E_\gamma)}{m\dot{m}^2}$
2.1	7.36e+39	1.52e+37	7.38e+39
2.2	1.26e+40	5.27e+37	1.27e+40
2.3	1.65e+40	1.04e+38	1.66e+40
2.4	1.92e+40	1.62e+38	1.94e+40
2.5	2.12e+40	2.23e+38	2.14e+40
2.6	2.26e+40	2.86e+38	2.29e+40
2.7	2.36e+40	3.48e+38	2.39e+40
2.8	2.42e+40	4.11e+38	2.46e+40
2.9	2.47e+40	4.61e+38	2.55e+40
3.0	2.49e+40	5.23e+38	2.54e+40
3.1	2.50e+40	5.72e+38	2.55e+40
3.2	2.49e+40	6.15e+38	2.55e+40
3.3	2.47e+40	6.80e+38	2.54e+40
3.4	2.45e+40	7.01e+38	2.52e+40
3.5	2.42e+40	7.50e+38	2.49e+40

Table 2: Selected values of $I(s, \alpha, \beta_{\text{adv}})/10^{40}$ for $\beta_{\text{adv}} = 0.5$

α	$s = 2.1$	$s = 2.3$	$s = 2.75$	$s = 3.3$
0.03	0.46	1.6	5.4	12.
0.1	.11	0.40	1.3	3.0
0.3	0.024	0.082	0.28	0.62

Table 3: Selected values of $I(s, \alpha, \beta_{\text{adv}})/10^{40}$ for $\beta_{\text{adv}} = 0.95$

α	$s = 2.1$	$s = 2.3$	$s = 2.75$	$s = 3.3$
0.03	0.88	3.2	10.	24
0.1	.15	.52	1.7	3.8
0.3	0.036	0.13	0.42	0.94

Table 4: Mass accretion rates required in Sgr A* in order to fit the observed γ -ray spectrum. The models assume $m = 2.45 \times 10^6$, $\alpha = 0.3$, $\beta_{\text{adv}} = 0.5$, and a power-law distribution of protons with index s .

s	\dot{m} ($m = 2.45 \times 10^6$)	\dot{M} (M_{\odot}/yr)
2.1	9.2×10^{-4}	5.2×10^{-5}
2.3	6.6×10^{-4}	3.5×10^{-5}
2.75	5.2×10^{-4}	2.8×10^{-5}
3.3	4.7×10^{-4}	2.5×10^{-5}

Table 5: Flux of photons > 100 MeV from various accreting black holes with ADAFs ($s = 2.75$).

Name	α	β_{adv}	m	\dot{m}	D_{kpc}	Flux (photons $\text{cm}^{-2} \text{s}^{-1}$)
Sgr A*	0.3	0.5	2.45×10^6	5.2×10^{-4}	8.5	4.9×10^{-7}
A0620–00	0.3	0.5	6	1.2×10^{-3}	1	2.8×10^{-9}
V404Cyg	0.3	0.5	12	4.6×10^{-3}	3	1.5×10^{-9}
NGC 4486	0.3	0.5	3×10^9	$10^{-2.5}$	16×10^3	6×10^{-9}
NGC 4258	0.3	0.95	3.6×10^7	10^{-2}	6.5×10^3	1.4×10^{-9}

Figure Captions.

Figure 1: γ -ray spectra from a thermal distribution of colliding protons for two different values each of α and β_{adv} .

Figure 2: γ -ray spectra from a power-law distribution of colliding protons for different values of the energy index s . The curves correspond to $\alpha = 0.3$, $\beta_{\text{adv}} = 0.5$. Tables 2 and 3 can be used to obtain fluxes for other values of α and β_{adv} .

Figure 3: γ -ray spectra from a thermal distribution of colliding protons in the Galactic Center source Sgr A*. The data correspond to EGRET observations of the unidentified source 2EG J1746-2852, which has been identified with Sgr A* (Merck et al. 1996).

Figure 4: Similar to Figure 3, but for a power-law distributions of proton energy. The curves correspond to different values of the proton spectral index $s = 2.1, 2.3$, and 2.75 . Note the significantly superior fit compared to Figure 3. The mass accretion rates of the various models are listed in Table 4.

Figure 1

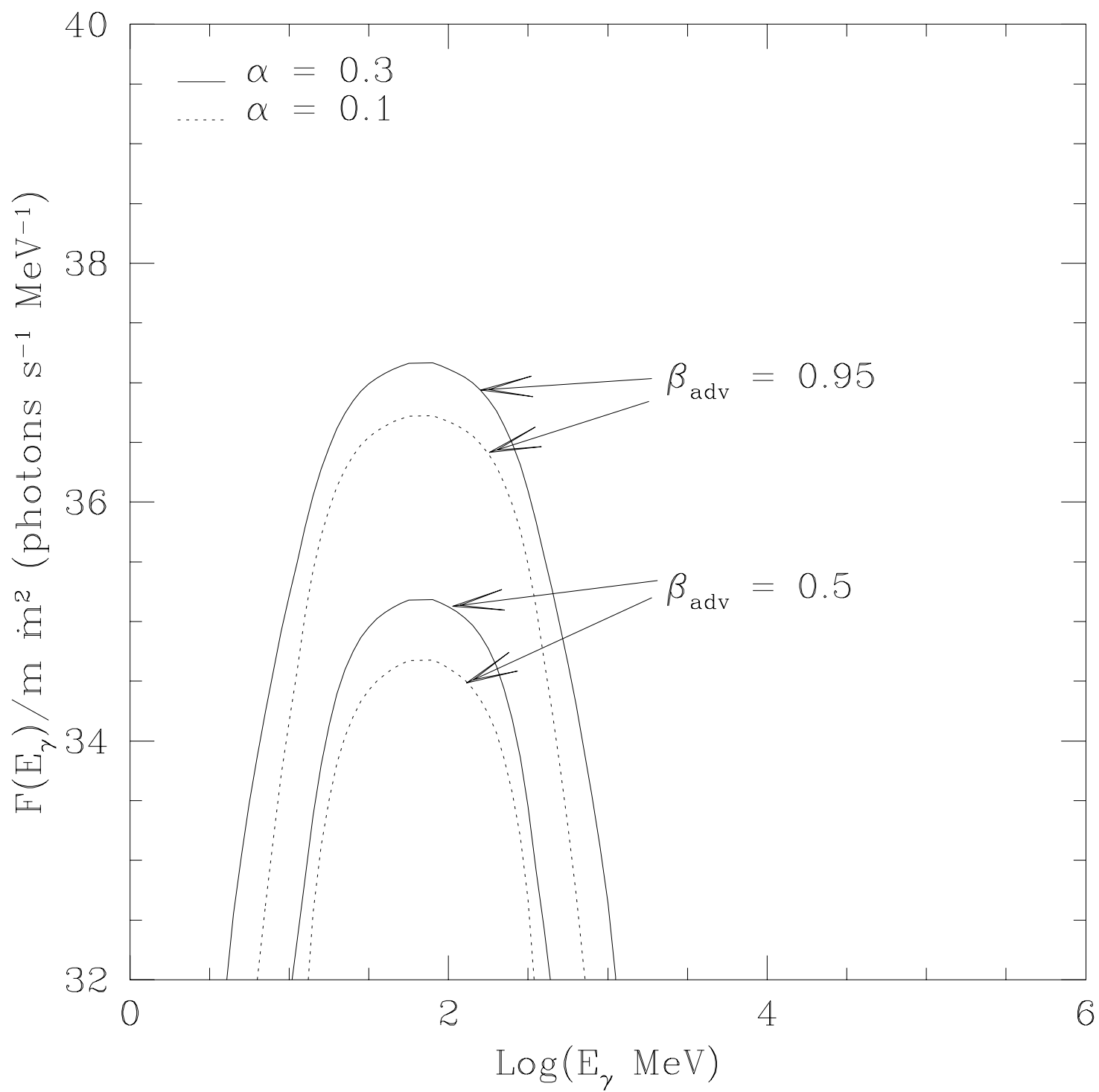


Figure 2

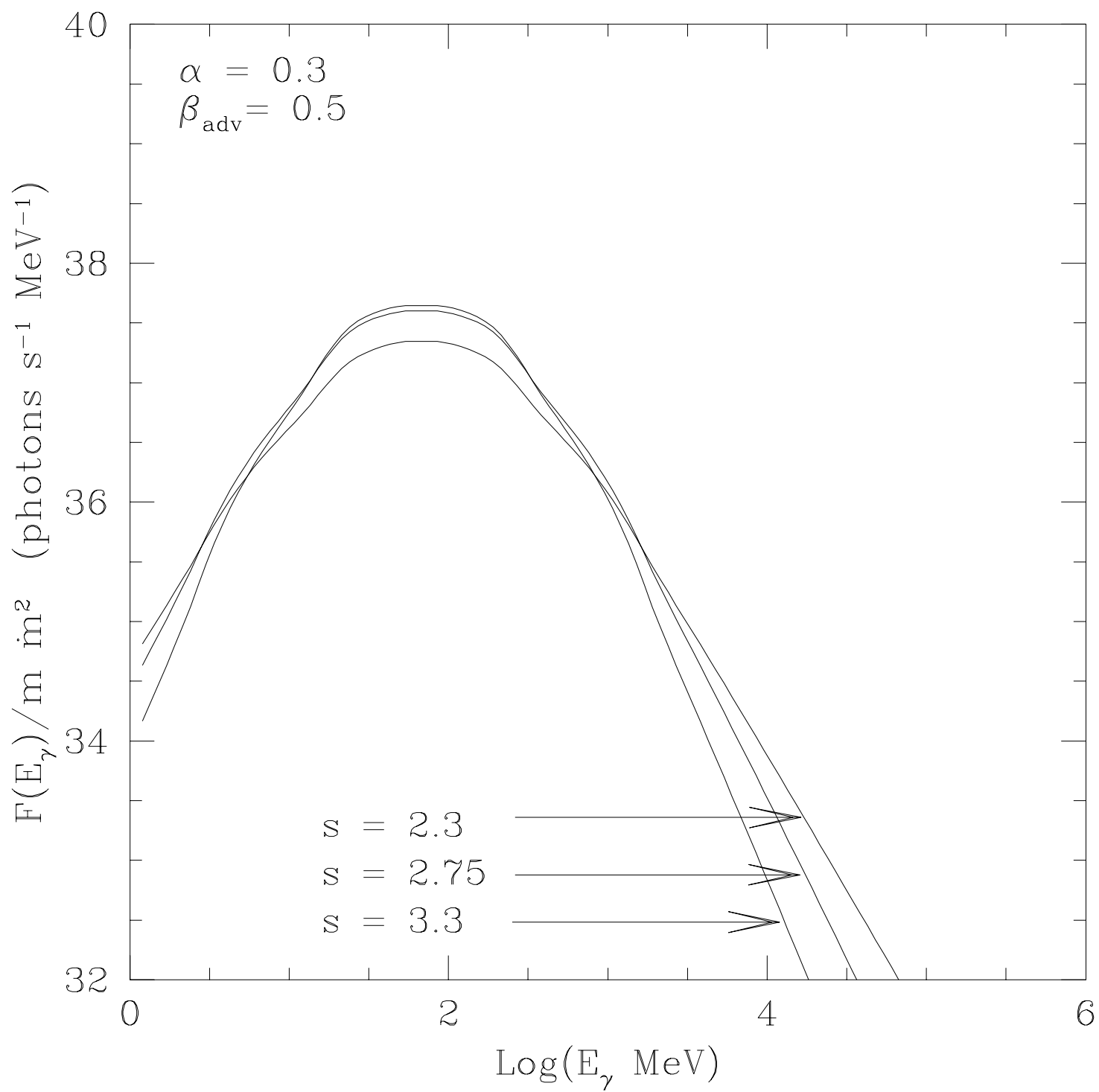


Figure 3

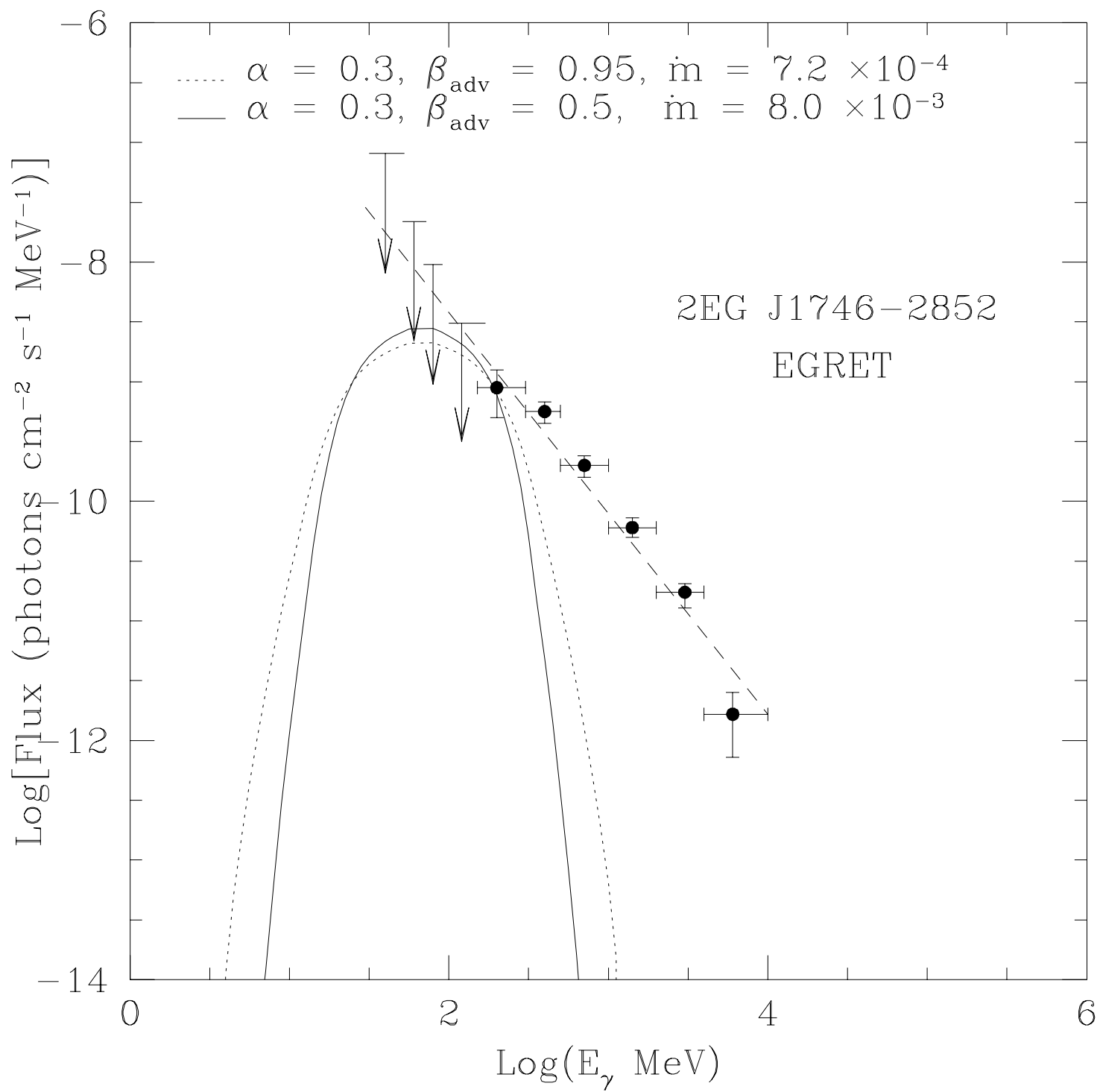


Figure 4

